

The Evolution of Gravitational Lens Galaxies

C.S. Kochanek¹, E.E. Falco¹, C.D. Impey², J. Lehár¹, B.A. McLeod¹,
H.-W. Rix³, C.R. Keeton², J.A. Muñoz¹ & C.Y. Peng²

Abstract. Most gravitational lens galaxies are early-type galaxies in relatively low density environments. We show that they lie on the same fundamental plane as early-type galaxies in both local and distant rich clusters. Their surface brightness evolution requires a typical star formation epoch of $z_f \simeq 2-3$, almost indistinguishable from that of rich cluster galaxies at comparable redshifts. The restricted galaxy type range of the lenses means that photometric redshifts work well even with only 1–3 filter photometry. We make preliminary measurements of the mass and luminosity functions of the lens galaxies, and find they are consistent with the standard model used for deriving cosmological limits using lens statistics. As expected for a mass-weighted sample, they are more massive and more luminous than the overall early-type galaxy population.

1. Introduction

Gravitational lens galaxies are a unique sample, because they are the only galaxies selected based on mass rather than luminosity. As such, the average properties of the lens galaxies are *identical* to the mass-weighted average properties of *all* galaxies at a given redshift. At intermediate redshifts ($0 < z_l < 1$), they are also the largest sample of galaxies with known masses outside the cores of rich clusters. Historically, the interpretation of the mass measurements has been hampered by a lack of accurate measurements of the *light*. Eliminating this rather peculiar problem for an astronomical sample is a primary goal of the CASTLES (CfA/Arizona Space Telescope Lens Survey) project (see Falco et al. in these proceedings).

If we combine accurate measurements of the mass and the light with the wide range of lens redshifts, then we have an excellent tool for studying the evolution of galaxy mass-to-light (M/L) ratios with redshift. Our method is similar to that introduced by van Dokkum & Franx (1996) and used by Kelson et al. (1997, 1999), van Dokkum et al. (1998, 1999), Pahre et al. (1999ab), and Jorgensen et al. (1999) to measure the evolution of early-type galaxies in rich clusters over the same redshift range. The lens galaxies are in far lower density environments than those in rich clusters – a “field” rather than a cluster

¹Harvard-Smithsonian Center for Astrophysics

²Steward Observatory, University of Arizona

³Max-Planck-Institut fuer Astronomie, Heidelberg

population – and theoretical models (e.g. Kauffmann 1996, Kauffmann & Charlot 1998) predict that they should have significantly younger stellar populations than galaxies in rich clusters. Studies of the colors and luminosity-effective radius correlations (e.g. Schade et al. 1996, 1999, Ziegler et al. 1999), and one small fundamental plane sample (Treu et al. 1999) all suggest that there is little difference between the field and cluster populations at $z \sim 0.5$. With the lens galaxies we can directly measure the surface brightness evolution to $z \simeq 1$.

In this review we summarize our recent results on galaxy evolution (Kochanek et al. 1999) and illustrate new results on the mass and luminosity functions of the lens galaxies. In §2 we introduce the fundamental plane (FP) of lens galaxies, which we use to determine the star formation epoch in §3 and as a photometric redshift estimator in §4. In §5 we determine the mass and luminosity function of the lenses as compared to local galaxies and simple statistical models, and in §6 we review our goals for the future.

2. The Fundamental Plane And Galaxy Evolution

The fundamental plane (FP) is a tight correlation between the central velocity dispersion σ_c , intermediate axis effective radius r_e , and central surface brightness μ_e discovered by Djorgovski & Davis (1987) and Dressler et al. (1987). The FP is a consequence of virial equilibrium, the nearly self-similar photometric and kinematic properties of early-type galaxies, and systematic rather than random variations in the metallicity and stellar population ages with mass or luminosity. As a tool for studying galaxy evolution, its key feature is that given any two of the three variables one can predict the remaining one. Traditionally this is done by comparing the directly measured effective radius r_e to that predicted by the FP,

$$\log(r_e^{FP}/h_{50}^{-1}\text{kpc}) = 1.24 \log(\sigma_c/\text{km s}^{-1}) + 0.33\mu_e(0) - 8.66 \quad (1)$$

using Jorgensen, Franx & Kjaergaard (1993, 1995ab, 1996, collectively referred to as JFK) renormalized to the closest HST filter (F606W). The only (rapidly?) evolving quantity appearing in the FP is the surface brightness, $\mu_e(z)$, through the time variation in the average luminosity of a stellar population. Hence, the standard FP is normalized using the surface brightness today, $\mu_e(z=0)$.

The key to studying galaxy evolution is the strong variation with redshift of $\mu_e(z)$ as compared to the invariance of r_e and σ_c . If we observe a galaxy in a series of filters j , we can measure the surface brightness μ_j , which evolves as

$$\mu_j(z) = \mu_j(0) + 10 \log(1+z) + e_j(z) + k_j(z) \quad (2)$$

where $\mu_j(0)$ is the surface brightness at $z=0$, the first redshift term is the $(1+z)^4$ cosmological dimming, $e_j(z)$ is the evolution correction for filter j , and $k_j(z)$ is the K-correction from the rest frame to the observed frame. If we can estimate the “final” surface brightness, $\mu_j(0)$, then we can directly measure the evolutionary terms. By simply reordering the standard form of the FP, we have

$$\mu_e^{FP}(0) = -3.76 \log(\sigma_c/\text{km s}^{-1}) + 3.03 \log(r_e/h_{50}^{-1}\text{kpc}) + 26.26, \quad (3)$$

so if we measure the effective radius and velocity dispersion of an early-type galaxy at any redshift, *we can predict the surface brightness it will have today*

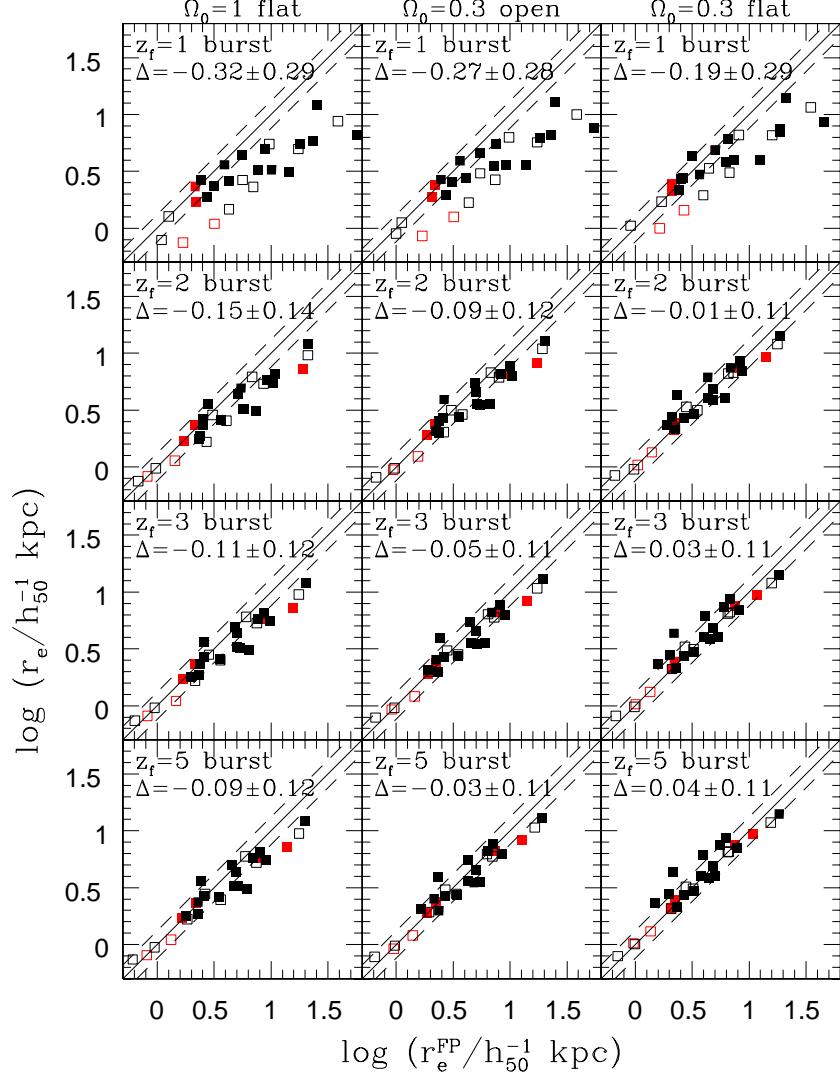


Figure 1. The FP of lens galaxies transformed to zero redshift. The cosmologies (from left to right) are the $\Omega_0 = 1.0$ flat, $\Omega_0 = 0.3$ open and $\Omega_0 = 0.3$ flat models. An instantaneous burst star formation history is used with star formation redshifts (from top to bottom) of $z_f = 1, 2, 3$ and 5 . The filled squares are for the lenses with known redshifts and for the open squares we have used photometric redshifts (see §4). The solid line marks the FP of the local comparison sample; 90% of the galaxies in the local JFK sample lie between the dashed lines. The mean residual ($\Delta = \langle \log(r_e/r_e^{FP}) \rangle$) and its dispersion are shown in the upper left corner of each panel. These are calculated using only the systems with known lens redshifts.

at $z = 0$. Thus, for any early-type galaxy we have that

$$e_j(z) + k_j(z) = \mu_j(z) - \left[\mu_j^{FP}(0) + 10 \log(1 + z) \right]. \quad (4)$$

We can determine $e_j(z)$ alone by measuring colors and interpolating to a fixed rest wavelength (van Dokkum & Franx 1996). The uncertainty for any one galaxy is not just the measurement uncertainty, as we must include the significant surface brightness scatter of the local FP (0.23 mag/arcsec² in JFK).

Our procedures differ somewhat from the cluster studies because we must consider individual lens galaxies rather than samples of cluster galaxies at a common redshift. The cluster studies measured the properties of enough galaxies in each cluster (6 on average) to use the standard FP (eqn. 1), measure the change in the zero-point (the 8.66) with redshift and then interpret it as evolution in the population averaged surface brightness or mass-to-light ratio. Since we cannot construct directly the FP of lens galaxies at any redshift we are driven to our alternate, galaxy by galaxy formulation. We believe, however, that our formulation of the analysis is the more physical. The existence of a thin FP at higher redshifts is observational evidence that early-type galaxies of similar mass have small age differences, but it is not required for the analysis.

For most lenses we do not have velocity dispersion estimates. We instead infer the velocity dispersion from the image separation $\Delta\theta$ assuming a singular isothermal sphere (SIS) mass distribution. Dynamical models of galaxies in SIS halos (Kochanek 1994) demonstrated that the dark matter dispersion, which we measure with $\Delta\theta$, is coincidentally almost identical to the central stellar dispersion. Adopting a normalization scale of $\sigma_{c*} = 225 \text{ km s}^{-1}$ for an L_* early-type galaxy (as required by models of the distribution of lensed image separations, Kochanek 1996, Falco et al. 1998), our velocity dispersion estimate becomes

$$\sigma_c = (225/f)(\Delta\theta/2''.91)^{1/2}(D_{OS}/D_{LS})^{1/2} \text{ km s}^{-1}, \quad (5)$$

where $f = \sigma_{dark}/\sigma_* \simeq 1.0 \pm 0.1$ is the normalizing factor between the velocity dispersion of the dark matter and the stars. We can also use the FP to estimate that its value is $f = 1.06 \pm 0.07$, providing further confirmation of the earlier dynamical and lensing results. We explored constant M/L dynamical models as well, but they generally fit the data poorly.

Our final current consists of 29 lenses, 12 of which are missing lens redshifts and 6 of which are missing source redshifts. Missing redshifts are the bane of lensing studies, and we discuss photometric redshift estimates for the lens galaxies in §4. The estimates of galaxy evolution and the photometric redshift estimates for the lens galaxies are insensitive to our assumptions about unmeasured source redshifts. We also analyzed a comparison sample of 54 galaxies from the cluster FP studies, so that we could compare the evolution of the two populations directly. For theoretical models we used the GISSEL96 versions of the Bruzual & Charlot (1993) spectral evolution models assuming $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. For simplicity we have compared the data to solar metallicity models with a single burst of star formation at redshift z_f . Models with extended bursts are also consistent with the data but require earlier star formation epochs.

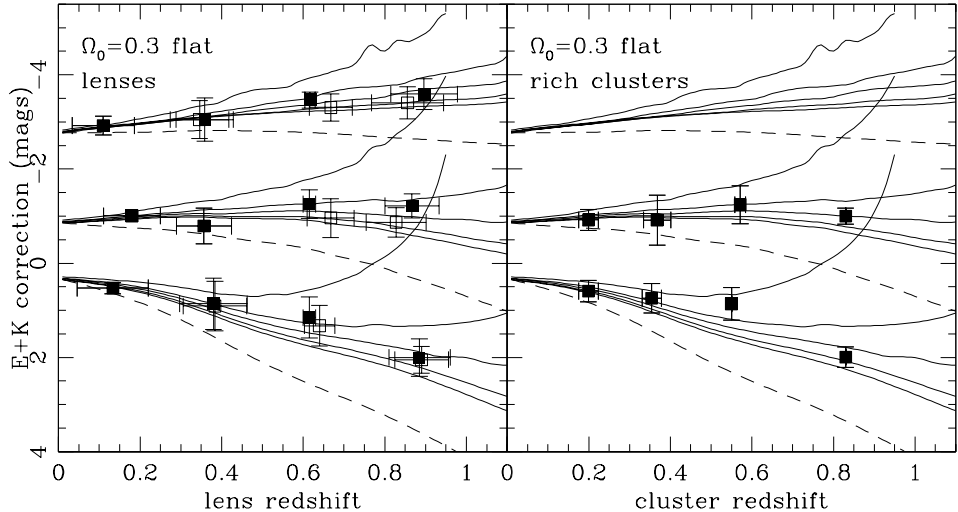


Figure 2. Evolution and K-corrections for the lens (left) and cluster (right) samples in the V=F555W (bottom), I=F814W (middle) and H=F160W (top) bands as a function of redshift for a flat $\Omega_0 = 0.3$ cosmological model. The zero-redshift colors were left in to separate the curves. The points are averages in redshift bins with edges at $z = 0.25$, 0.50 and 0.75 . The error bar on the E+K correction is the standard deviation of the galaxies in the bin, not the uncertainty in the mean. For the lenses, the filled points are the averages using only the lenses with known redshifts, while the open points include all lenses. The dashed curves are the no evolution models for each filter, and the solid curves are the instantaneous burst models with star formation redshifts (from bottom to top) of $z_f = 10, 3, 2, 1.5$ and 1.0 respectively.

3. The Star Formation Epoch of Early-Type Galaxies

The lens galaxies at any given redshift are a mass-weighted sample of *all* galaxies at that redshift. This means that the mean star formation epoch of the lens galaxies is closely related to the mean, mass-weighted star formation epoch of all galaxies. Hence, the star formation epoch of the lens galaxies is a far more fundamental measurement than the star formation epoch of galaxies in rich clusters. While we consider only early-type lenses here, they are the vast majority of all lenses. Moreover, even the late-type lenses tend to be fairly red and show few signs of active star formation. The absence of the numerous, luminous, blue, low-mass star forming galaxies in the lens sample confirms that these galaxies make a negligible contribution to the total mass in stars.

We can show that the lens galaxies lie on a coherent FP by evolving their properties forward in time and placing them on the present day FP. The transformations depend on the star formation epoch, z_f , and the cosmological model (Ω_0 and λ_0). Figure 1 shows the results. The mean logarithmic residual, $\Delta = \langle \log r_e / r_e^{FP} \rangle$, is computed only for the lenses with known redshifts. As van Dokkum & Franx (1996) first noted, it is difficult to reconcile the high

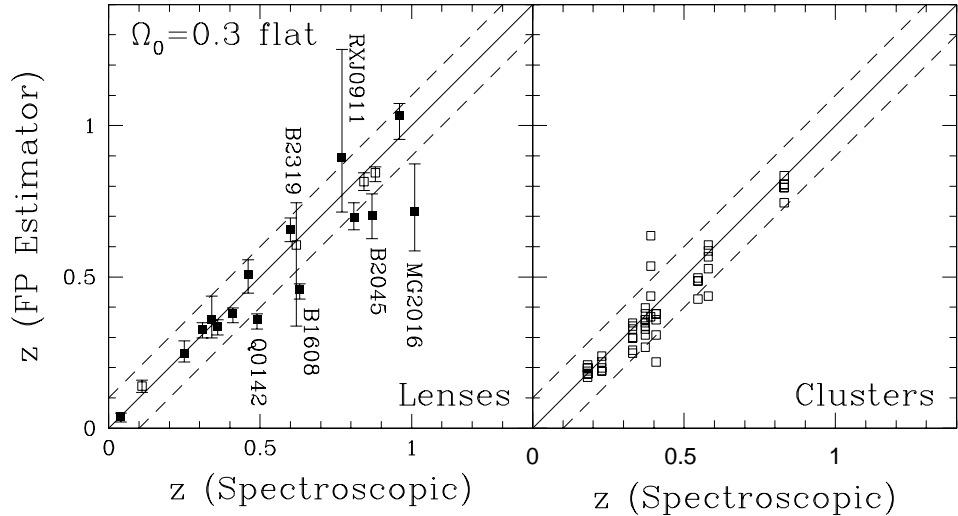


Figure 3. The FP redshift estimates compared to the spectroscopic redshifts. The left panel shows the results for the lens galaxies, and the right for the cluster galaxies. For the lens galaxies, solid (open) points are used for lenses where the source redshift is known (unknown). The dashed lines are offset by $|\Delta z| = 0.1$ to illustrate the desired accuracy. We have only H-band data for the labeled lenses with large redshift uncertainties (RXJ 0911+0551, MG 2016+112, B 2045+265 and B 2319+052).

Ω_0 models with a reasonable star formation epoch ($z_f \lesssim 10$). For the low Ω_0 models, a coherent FP matching the local observations is possible for formation epochs $z_f \gtrsim 2$. The scatter about the FP is comparable to that for the local FP, so the lens galaxies cannot have an enormous range of formation epochs.

Since we are now confident that the lenses lie on the FP, Figure 2 shows the evolution of the E+K corrections with redshift for both the lens and cluster samples in the $\Omega_0 = 0.3$ flat cosmological model. The results for an $\Omega_0 = 0.3$ open model are similar. The dominant term depends on the wavelength. In the V band, the K-correction dominates and the galaxies rapidly fade, in the I band, the E and K corrections balance, and in the H-band, the evolution dominates and the galaxies steadily become brighter. At all bands, the galaxies become steadily brighter than predicted by a no evolution model.

It is difficult to distinguish the evolution of the lens and cluster galaxies, and both samples favor star formation epochs of $z_f \simeq 2-3$. This strongly contradicts the predictions of Kauffmann & Charlot (1998), where most of the field early-type galaxies form their stars at $z_f \lesssim 1$. Somerville & Primack (1998) have argued more generally that the earlier semi-analytic models systematically underestimated the epoch of star formation through their choice of star formation mechanisms. In their defense, Kauffmann & Charlot (1998) would argue that morphologically selected early-type galaxies look old at all redshifts because the mergers required to produce the early-type morphologies do not occur when the stellar populations are young. This requires rapid number evolution

in the early-type galaxy population to $z = 1$, which is probably inconsistent with observations (Lilly et al. 1995, Schade et al. 1999). Moreover, the lens galaxies were selected based on mass, not morphology, and while we excluded a few late-type galaxies, there is no significant population of blue, star-forming lenses which we have dropped from the analysis.

4. Photometric Redshifts

Redshift incompleteness is the bane of many astrophysical applications of gravitational lenses, even though there is no technical barrier to measuring most of the missing redshifts in the age of the 8 meter telescope. This is unfortunate, because you obtain more cosmological information with the measurement of a lens redshift than any other single object. For example, the distribution of lens redshifts is a powerful cosmological test (Kochanek 1992), but it requires high redshift completeness because it is very difficult to make a statistical model for incomplete redshift samples. The difficulty in measuring lens redshifts is further evidence that the stellar populations of lens galaxies are old. If the typical lens had any ongoing star formation, the redshift measurements would be far easier due emission lines usually associated with star formation.

Photometric redshifts should work well for lens galaxies because of the restricted galaxy type distribution (mostly early-type galaxies, and no funny dwarf galaxies) and because we also know the galaxy masses. We have developed a redshift estimation method based on the FP. Placing a galaxy on the FP can accurately estimate a galaxy redshift with *no* color information if the lens has $z_l \lesssim 0.5$ or we have optical photometry. If we have color information, particularly a color bracketing the 4000Å spectral break, then the color information constrains the redshift more strongly than the FP. Figure 3 tests the accuracy of the method by comparing the photometric redshift estimates to the known spectroscopic redshifts for the lens and cluster galaxies. Keep in mind that these estimates are made with 1–3 filter photometry.

For the lens galaxies, all the poor estimates with large redshift uncertainties are lenses at $z_l > 0.5$ for which we have only infrared photometry. With the addition of any optical data the uncertainties collapse and the prediction usually matches the measured redshift. In a few cases (Q0142–100 and B1608+656 in Fig. 3), we have accurate 3-filter photometry and small redshift uncertainties, but the predicted redshift is incorrect. For B1608+656, the problem is that the galaxy is an E+A galaxy with more recent star formation (Myers et al. 1995). The average accuracies, $\langle z_{FP} - z_{true} \rangle$, are -0.03 ± 0.10 and -0.02 ± 0.07 for the lens and cluster galaxies respectively. Much of the scatter for the lens galaxies is due to the systems with only H-band data.

5. The Mass and Luminosity Function of Lens Galaxies

The lens sample is large enough to begin studying the luminosity and mass functions of the lens galaxies. The average image separation of the lenses is already the most accurate way of estimating the mean velocity dispersion of massive galaxies, which makes matching the image separations a critical component of any estimate of the cosmological model using gravitational lens statistics.

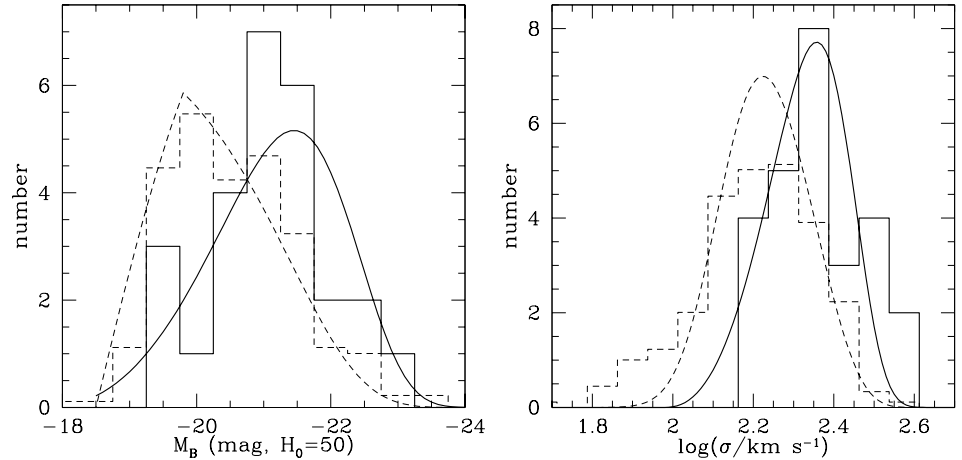


Figure 4. The luminosity (left) and velocity (right) functions of lens galaxies compared to local clusters. The heavy solid (light dashed) histograms show the observed distributions of the lens (cluster) galaxies, and the heavy solid (light dashed) curves show the predicted distributions for the lens (cluster) galaxies. The sharp feature in the predicted luminosity function for the cluster galaxies is created by our *ad hoc* model for the magnitude limits in the JFK sample of cluster galaxies.

Because the lenses are a mass-weighted galaxy sample, they should be more luminous and more massive than a magnitude limited sample of cluster galaxies. We can make a preliminary comparison by assuming the standard model we have used for gravitational lens statistics (Kochanek 1996, Falco et al. 1998).

We start with a standard Schechter luminosity function to count the galaxies,

$$dn/dL = (n_*/L_*)(L/L_*)^\alpha \exp(-L/L_*), \quad (6)$$

combined with a Faber-Jackson law to relate luminosity and velocity dispersion,

$$L/L_* = (\sigma/\sigma_*)^\gamma, \quad (7)$$

where the velocity dispersion is related to the image separation through eqn. (5). The multiple imaging cross section, $\propto \Delta\theta^2 \propto \sigma^4 \propto L^{4/\gamma}$, is used to compute the probability that a galaxy acts as a lens. We fix the parameters to the standard model we have used to study lens statistics ($\gamma = 4$, $\alpha = -1$, $\sigma_* = 225 \text{ km s}^{-1}$, and $B_* = -19.9 + 5 \log h \text{ mag}$). The galaxy density n_* will be nearly degenerate with the cosmological model, so we will not examine it here.

Both the lens and cluster galaxy samples are affected by selection effects. For the local JFK cluster galaxy sample, it is the magnitude limit of the sample, which we have treated only approximately. For the lens galaxies, the only important selection effect is the finite angular resolution of the surveys, which we include as a minimum detectable separation $\Delta\theta_{min}$. The minimum separation leads to a minimum lens luminosity $L_{min}/L_* = (\Delta\theta_{min}/\Delta\theta_*)^{\gamma/2}$ and a selection function $S(x = L/L_{min}) = x^3(10 - 15x + 6x^2)$. Combining all these effects and

using our standard parameter values, the distribution of all early-type galaxies is

$$dn/dM \propto dn/d\log \sigma \propto \exp(-L/L_*) \quad L > L_{min} \quad (8)$$

where L_{min} is set by the survey magnitude limit, and the distribution of lens galaxies is

$$dn/dM \propto dn/d\log \sigma \propto (L/L_*) \exp(-L/L_*) S(L/L_{min}) \quad (9)$$

where L_{min} is set by the survey resolution. For the local cluster sample, the distribution of galaxies peaks at the luminosity L_{min} corresponding to the sample magnitude limit. The lens galaxy sample peaks at $L \simeq L_*$, while the selection function matters only near $L_{min} \simeq 0.05L_*$. In fact, our model for the selection function of the lens galaxies is better than that for the JFK cluster galaxies. The results are shown in Figure 4, where we present histograms of the observed lens and JFK cluster galaxy distributions as compared to our simple model. As expected, the lens galaxies are both more luminous and more massive than typical early-type galaxies. More importantly, the differences closely match the predictions of our standard model.

6. Future Growth

This is only an interim report on studies of the distribution and evolution of galaxies using gravitational lenses, since we have used only half the known lenses and the number of lenses is still growing rapidly. Our progress is limited by two major problems. First, despite our best efforts, only about 70% of the lenses have archival or scheduled HST images good enough to do surface photometry of the lens galaxy even under a generous definition of “good enough.” Accurate measurements of galaxy evolution, mass-to-light ratios, luminosity and mass functions require higher precision data than the fractional-orbit snapshots commonly used to confirm lens candidates. Host galaxy contamination, while scientifically valuable (see Bernstein et al. and Rix et al. in these proceedings), is also a serious problem for many radio lenses. Second, the high level of redshift incompleteness is a major barrier to using gravitational lenses as astrophysical tools. Even so, the sample of 30 early-type galaxies we used to study galaxy evolution is 5 times larger than the biggest published sample of field early-type galaxies with kinematic measurements at comparable redshifts. We hope to solve the first problem with the continuation of the CASTLES project into HST Cycle 9, and the missing redshift problem should soon be solved by the advent of so many new large telescopes.

Acknowledgements: Support for the CASTLES project was provided by NASA through grant numbers GO-7495 and GO-7887 from the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

References

Bruzual, A.G., & Charlot, S., 1993, ApJ, 405, 538

- Djorgovski, S.G. & Davis, M., 1987, *ApJ*, 313, 59
- Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R.L., Faber, S.M., Terlevich, R.J. & Wegner, G., 1987, *ApJ*, 313, 42
- Falco, E.E., Kochanek, C.S. & Muñoz, P., 1998, *ApJ*, 494, 47
- Jorgensen, I., Franx, M. & Kjaergaard, P., 1993, *ApJ*, 411, 34
- Jorgensen, I., Franx, M. & Kjaergaard, P., 1995a, *MNRAS*, 273, 1097
- Jorgensen, I., Franx, M. & Kjaergaard, P., 1995b, *MNRAS*, 276, 1341
- Jorgensen, I., Franx, M. & Kjaergaard, P., 1996, *MNRAS*, 280, 167
- Jorgensen, I., Franx, M., Hjorth, J., & van Dokkum, P.G., 1999, *astro-ph/9905155*
- Kauffmann, G., 1996, *MNRAS*, 281, 487
- Kauffmann, G. & Charlot, S., 1998, *MNRAS*, 294, 705
- Kochanek, C.S., 1992, *ApJ*, 384, 1
- Kochanek, C.S., 1994, *ApJ*, 436, 56
- Kochanek, C.S., 1996, *ApJ*, 466, 638
- Kochanek, C.S., Falco, E.E., Impey, C.D., Lehar, J., McLeod, B.A., Rix, H.-W., Keeton, C.R., Munoz, J.A., & Peng, C.Y., 1999, *astro-ph/9909018*
- Kelson, D.D., van Dokkum, P.G., Franx, M. & Illingworth, G.D., 1997, *ApJL*, 478, L13
- Kelson, D.D., Illingworth, G.D., van Dokkum, P.G., & Franx, M., *astro-ph/9908257*
- Lilly, S.J., Treese, L., Hammer, F., Crampton, D., & Le Fevre, O., 1995, *ApJ*, 455, 108L
- Myers, S.T., Fassnacht, C.D., Djorgovski, S.G., et al., 1995, *ApJL*, L5
- Pahre, M.A., Djorgovski, S.G., & de Carvalho, R.R. 1999a, *ApJS* submitted
- Pahre, M.A., Djorgovski, S.G., & de Carvalho, R.R. 1999b, *ApJL* submitted
- Schade, D., Carlberg, R.G., Yee, H.K.C., Lopez-Cruz, O. & Ellingson, E., 1996, *ApJL*, 464, L63
- Schade, D., Lilly, S.J., Crampton, D., et al., 1999, *astro-ph/9906171*
- Somerville, R.S., & Primack, J.R., 1998, *astro-ph/9811001*
- Treu, T., Stiavelli, M., Casertano, S., Moller, P., & Bertin, G., 1999, *MNRAS* in press, *astro-ph/9904327*
- van Dokkum, P.G. & Franx, M., 1996, *MNRAS*, 281, 985
- van Dokkum, P.G., Franx, M., Kelson, D.D. & Illingworth, G.D., 1998, *ApJL*, 504, L17
- van Dokkum, P.G., Franx, M., Fabricant, D., Kelson, D.D. & Illingworth, G.D., 1999, *ApJL*, 520, 95
- Ziegler, B.L., Saglia, R.P., Bender, R., Belloni, P., Greggio, L., & Seitz, S., 1999, *A&A*, 346, 13